"Interaction-Free" Measurements: The In's and Out's of Quantum Interrogation

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For those of us familiar with quantum mechanics, it is common belief that a measurement on a system will necessarily disturb it (unless the system is already in an eigenstate of the measurement observable). This makes the concept of "interaction-free" measurements all the more intriguing. By incorporating the principle of complementarity and the "quantum Zeno effect," one can in fact achieve just such a measurement, in which the presence of an opaque object is determined optically, but with a negligibly small chance that the object absorbs or scatters any light in the process.

The idea was first proposed several years ago by Elitzur and Vaidman. They suggested using a simple interferometer, balanced so that an incident photon would always exit to a particular output port—the other port would remain dark due to complete destructive interference of the two paths in the interferometer; here a wave-like description is appropriate. However, the presence of an object in one arm will disrupt this interference. Now a particle-like description is more appropriate to account for the distinguishable trajectories of the photon. At the first beamsplitter, the photon has a 50% probability to take the path containing the object and be absorbed. But half the time the photon will take the other path; moreover, at the second beamsplitter, there is no longer any interference, so the photon will have a net 25% chance of going to the previously dark port. A "click" at the detector in this port unambiguously indicates the presence of the object, even though the photon could not have taken the path containing the detector (for then it would have been absorbed). Such measurements were termed "interaction-free," although the *possibility* of an interaction is crucial.

We have modified the basic idea of Elitzur and Vaidman to incorporate the possibility of *imaging*. A schematic of our setup is shown in Fig. 1. A photon polarized at 45° is incident on a polarizing Mach-Zehnder interferometer. The first polarizing beamsplitter transmits the horizontal component of the light and reflects the vertical component. These two are then recombined at the second polarizing beamsplitter. The polarization of the light is then measured in the 45/-45° basis. If the two paths are unimpeded and the path lengths are the same, then the light will still be polarized at 45°. If, on the other hand, there is an object in the vertical-polarization arm, then any light leaving the interferometer will be horizontally polarized, and hence will have a 25% chance of being detected by the -45° detector, an "interaction-free" quantum interrogation. By including a focusing lens before the interferometer and a similar collecting lens after it, we were able to create a small beam waist, through which we scanned a variety of ~one-dimensional objects, such as hairs, wires, optical fibers, *etc.* A typical example is shown in Fig. 2. With this system we were able to achieve a resolution of about 10 μm.

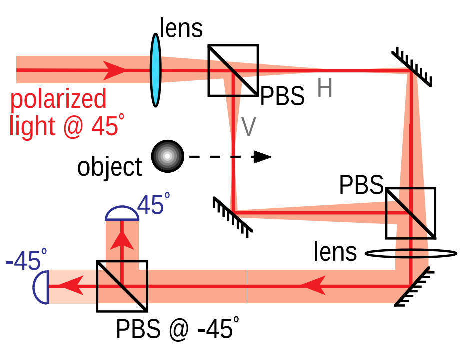


***Fig. 1** Schematic of experimental setup to demonstrate the principle of "interaction-free" measurements, modified to allow one-dimensional imaging.*

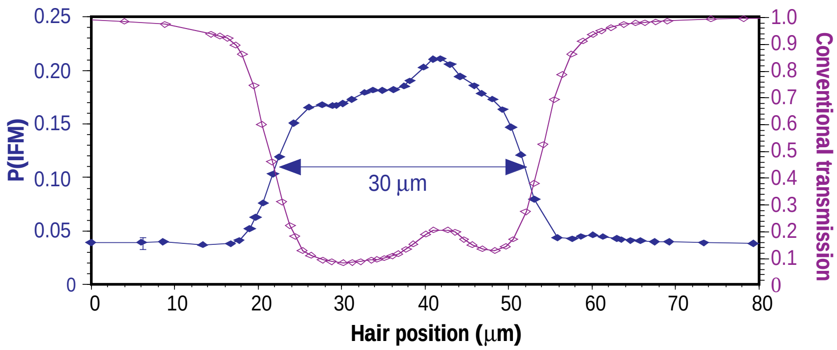


Fig. 2 Scan of a hair through the system shown in Fig. 1. The open purple symbols are a standard measurement of the hair transmission; the filled blue symbols are the "interaction-free" profile of the hair.

One immediate problem of the system proposed by Elitzur and Vaidman is that the object still absorbs the photon some fraction of the time. In fact, by varying the reflectivities of the interferometer beamsplitters (or by varying the input and analysis polarization in our imaging setup), one can affect the efficiency of the technique (see Fig. 3). Nevertheless, one can never get an efficiency over 50%, *i.e.*, at most half of the measurements will be "interaction-free."

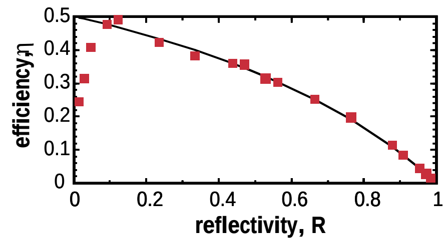


Fig. 3 The measured efficiency of the Elitzur-Vaidman technique as the effective reflectivity of the beamsplitters is varied. The solid curve is the theoretical prediction. The deviation of the experimental results for small reflectivities is due to unavoidable "crosstalk" in the polarizing beamsplitters (i.e., *a small amount of horizontally-polarized light is reflected).*

Along with collaborators at the University of Innsbruck in Austria, we have discovered a way in which one can in principle achieve efficiencies arbitrarily close to 1 (*i.e.*, the probability of absorption by the object can be arbitrarily small). A new quantum phenomenon must be utilized, namely the Quantum Zeno effect. A simple optical example is shown in Fig. 4a. A single horizontally-polarized photon is directed through a series of N polarization rotators (for concreteness we could imagine using an optically-active sugar solution), each of which rotates the polarization by $\Delta\theta = \pi/2N$; thus upon exiting the system, the photon now has

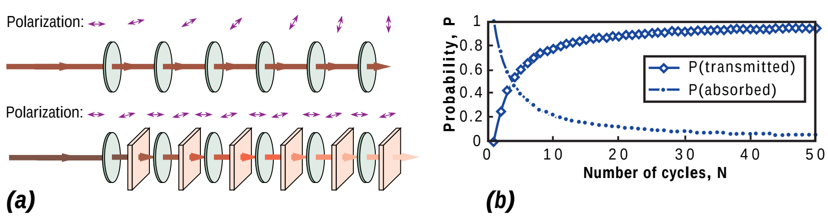


Fig. 4 (a) The quantum Zeno effect. In the top image, a single photon with horizontal polarization is rotated stepwise to vertical by a series of polarization rotators (green disks). The bottom image shows how this quantum evolution may be inhibited by interspersing a series of horizontal polarizers (red squares), which continually project the photon back into its original state. (b) Calculated probabilities of transmission and absorption through the system, as a function of the number of cycles.

vertical polarization. We may inhibit this stepwise evolution by making a measurement of the polarization at each stage. This may be accomplished by inserting a horizontal polarizer after each rotation element. Since the probability of being transmitted through each polarizer is just $\cos^2(\Delta\theta)$, the probability of being transmitted through all N of them is simply

$$\cos^{2N}(\Delta\theta) = \cos^{2N}(\pi/2N) \approx 1 - \pi^2/4N,$$

and the complementary probability of absorption is $P(abs) \approx \pi^2/4N$ (see Fig. 4b). Hence, by increasing the number of cycles, one can in principle have an arbitrarily small probability that the photon is absorbed by one of the polarizers, and yet, because the photon exits the system still in its initial horizontal polarization state, we know the polarizers are present.

Obviously the system from Fig. 4a is of limited use because it only works with polarizing objects. To be able to make a quantum interrogation of *any* nontransmitting object, one needs a hybrid solution. We have developed and tested such a system. The basic concept is shown in Fig. 5. A single photon is made to circulate N times through the setup before it is somehow removed and its polarization analyzed. As in the Zeno example, the photon initially has horizontal polarization, and is rotated by $90°/N$ on each passage through the rotator. In the absence of any object, the polarization-interferometer has absolutely no effect on the polarization of the light; it merely breaks the light into its horizontal and vertical components and adds them back with the same relative phase. Hence, if there is no object, after N cycles the photon is found to have vertical polarization. On the other hand, if there *is* an object in the vertical arm of the interferometer, only the horizontal component of the light is passed, *i.e.*, each *non*absorption by the object—with probability $\cos^2(\Delta\theta)$—projects the wavefunction back into its initial state. In this case, after N cycles, either the photon will still have horizontal polarization, unambiguously indicating the presence of the object, or the object will have absorbed the photon. And by going to higher N, the probability of absorption can in principle be made arbitrarily small.

To demonstrate this phenomenon in an actual experiment, several modifications were made (see Fig. 6). First, a horizontally-polarized pulsed laser was coupled into the system by a highly reflective mirror. The light was attenuated so that the average photon number per pulse after the mirror was only ~0.3. The photon then bounced several times between this recycling mirror and one of the mirrors making up a Michelson polarization interferometer (like a normal Michelson interferometer, but with a polarizing

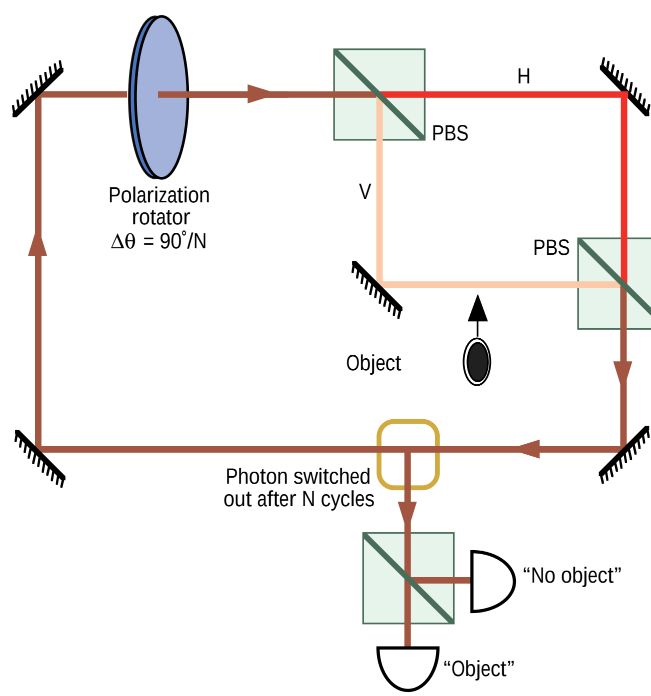


***Fig. 5** Simplified schematic of a hybrid system, combining the quantum Zeno effect with a polarization interferometer to allow >50% efficient interaction-free measurements.*

beamsplitter instead). At each cycle the polarization was rotated by a specific amount, and after the desired number of cycles the photon was switched out of the system using the high-voltage Pockel's cells in the interferometer arms. The photon was then analyzed using an adjustable polarizer, and detected by a single-photon detector. In the absence of any object in the vertical arm of the interferometer, the polarization was found to be essentially vertical, indicating that the stepwise rotation of polarization had taken place. In the presence of the object, this evolution was inhibited, and the photons exiting the system were still horizontally-polarized, an interaction-free measurement of the presence of the object. The fraction of measurements that were interaction-free was measured as the number of cycles N was increased (and the rotation angle, $\Delta\theta$, was correspondingly decreased).

Rather unexpectedly, we found that after an initial increase in efficiency, the efficiency actually decreased toward zero past some optimal number of cycles. A detailed theoretical calculation verified that this decrease arises due to loss in the system: basically, a photon that makes it to the detector experiences the single-cycle loss N times, while a photon that is absorbed by the object (which may happen at any cycle), experiences this loss only ~$N/2$ times. The net effect is to reduce the efficiency for high-cycle numbers

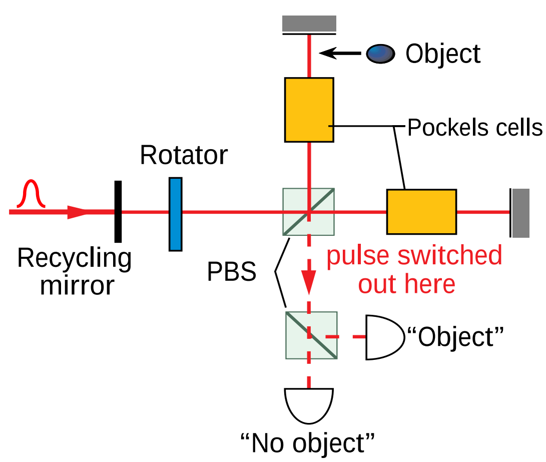
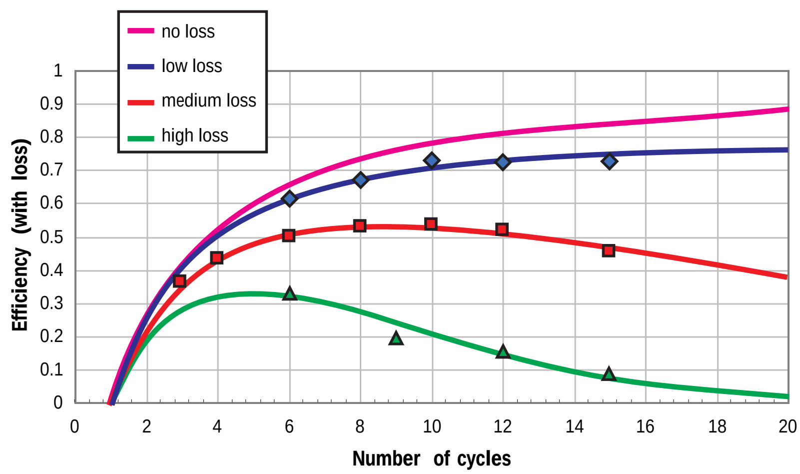


***Fig. 6** Experimental setup to demonstrate high-efficiency quantum interrogation. A photon remains in the system for N cycles, at which time the Pockel's cells are activated and the light is switched out. The polarization of the exiting photons depends on whether or not an object is blocking the vertical-polarization arm of the interferometer.*

rather than having it asymptote to 1. Figure 7 shows the experimental verification of this phenomenon, as well as the theoretical predictions, which are in good agreement. Despite this effect, we were able to observe efficiencies of up to 73%, which means that the presence of the object could be ascertained with only one-fourth of a photon being absorbed. Ours was the first measurement to break the 50% limit of the simple Elitzur-Vaidman technique. In addition, we have made measurements which confirm the feasibility of efficiencies up to 85%. And we now think we have a method to improve our system so that the probability of absorption could be as low as 1–2%. If these methods could be combined with the imaging techniques already explored, one would have a very useful tool for noninvasive diagnostics, *e.g.*, of delicate biological specimens or even photosensitive chemical reactions.

Another very interesting area we are studying is the possibility of making such quantum interrogations of truly quantum mechanical objects, such as single atoms or ions. The advantage of this is that the quantum object can be readily prepared into a superposition of states, one of which is sensitive to the "interaction-free" measurement technique, and one of which is not. Theoretical calculations predict that the state of the light and the state of the object will then become quantum mechanically *entangled*. Remarkably, it seems that this will be true even for light pulses containing several photons. If the object were measured to be in its

Fig. 7 Plot of experimentally measured efficiency versus number of cycles for several different values of loss.



initial state, one would then have a multiphoton pulse of light, in a superposition of horizontal and vertical polarization. This is an example of a Schrödinger cat and would open the door to a whole range of fundamental experiments on the nature of decoherence. It would also help to answer the question of why we do not observe macroscopic quantum superpositions in our everyday lives, even though we believe that quantum mechanics is a correct description of nature. One practical application of these interaction-free measurements of quantum objects is as a sort of quantum "interface" for connecting together different quantum computers (a separate research highlight addresses our contributions to quantum computation).

Further Reading

P. G. Kwiat, "Experimental and Theoretical Progress in Interaction-Free Measurements," *Physica Scripta* T76, 115 (1998).

P. G. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger, and M. A. Kasevich, "Interaction-Free Measurement," *Physical Review Letters* 74, 4763 (1995).

P. G. Kwiat, H. Weinfurter, and A. Zeilinger, "Interaction-Free Measurement of a Quantum Object: On the Breeding of 'Schrödinger Cats,'" in *Coherence and Quantum Optics VII*, J. Eberly, L. Mandel, and E. Wolf, Eds. (Plenum Publishing, 1996).

P. G. Kwiat, H. Weinfurter, and A. Zeilinger, "Quantum Seeing in the Dark," *Scientific American*, November 1996, pp. 52–58.

A. G. White, J. R. Mitchell, O. Nairz, and P. G. Kwiat, "'Interaction-Free' Imaging," *Physical Review A* 58, 605 (1998).